

MOLD FOR OPTICAL COMPONENTSFIELD OF THE INVENTION

[0001] The present invention relates generally to a system and method for manufacturing and/or refining a surface, as well as to devices manufactured using this system and/or method. More particularly the system and method may be used to produce high-precision optical lens molds using a laser ablation process.

BACKGROUND OF THE INVENTION

[0002] The use of molds in modern manufacturing of devices is a well known process dating back to ancient times. Most recently, however, precision mold castings have been used by optical equipment manufacturers in the production of optical lenses. Devices incorporating one or more of optical imaging, optical telecommunications, and optical data storage technologies are becoming increasingly prevalent. Many of these products use one or more optical lenses. Consequently, it is highly desirable that the optical lenses used in various devices meet their design specifications as precisely as possible. It may also be desirable to maintain economically feasible manufacturing methods in the production of such lenses so that the lenses may be desirably priced in the marketplace.

[0003] As demand for high performance optical equipment has grown, devices have become smaller and more precise. As a result, these devices require difficult-to-manufacture high-precision optical lenses in order to meet performance requirements. The Blu-Ray optical storage standard, for example, uses a short wavelength laser (blue laser) to allow more data to be stored on optical storage discs, as opposed to current standards (CD, DVD) that use red laser light. The shorter wavelength laser requires a smaller, more precise lens with desirably minimal imperfections on the surface thereof.

[0004] A current method of manufacturing high-precision lenses is illustrated in Figures 1A and 1B, and includes forming a mold cavity 2 into a hard mold material 1, where the mold cavity 2 matches the lens design of a desired optical lens geometry. The mold cavity 2 is generally ground and/or cut from the mold material 1 using at least one of a diamond grinding wheel 10 (shown in Figure 1A and 1B) attached to a movement arm 14 or a diamond turning point 12 (shown in Figure 2) that perform a predetermined carving algorithm 16 (exemplary, as shown in Figures 1A, 1B, and 2). After the final mold is finished, optical lens material is set inside of the mold and desirably pressed under high temperature and pressure in order to form the optical lens (not shown in Figure 1). Those skilled in the art will recognize that other methods may be used with the final finished mold to form an optical lens.

[0005] It is generally possible to achieve a design precision of around ± 0.1

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1 microns using the prior art method described above. However, the grinding/cutting
2 process introduces mold cavity surface errors that do not meet nanometer and sub-
3 nanometer precision required by high-precision optical lenses, such as those needed for
4 the Blu-ray standard. As illustrated in Figures 1A and 1B, the surface errors are as a
5 result of undesirable bending of the shank 14 of the movement arm and vibration of
6 the shank 14 and/or the grinding wheel 10. As shown in Figure 2, similar defects may
7 be caused by bending or vibration of the shaft 20 and/or diamond turning point 12.
8 Undesirable defects may also result from temperature- or pressure-induced changes at
9 the turning point-cavity surface interface 24, as well as the inherent imprecision of
10 mechanical manufacturing tools (not shown in Figure 2). Furthermore, the grinding
11 wheel/turning point experiences wear and may become less accurate after prolonged
12 use, introducing undesirable manufacturing costs in their replacement and in extra
13 machining of the mold.

14 **[0006]** Additionally, an optical lens mold 31 having a cavity 32 may be desirably
15 finished with the application of a thin film 33 over at least the cavity 32 (as shown in
16 Figure 3). The application of the thin film may, for example, prevent undesirable
17 bonding between optical lens material and mold 31 during the pressing process. The
18 application of the thin film, however, may also introduce undesirable undulations on the
19 thin film surface, thereby introducing additional errors to the manufacturing process of
20 high-precision lenses.

21 **[0007]** Current methods aimed at reducing errors in optical lens manufacturing
22 generally involve the production of an optical lens mold, as described above, from
23 which an imperfect optical lens is produced. Then, an optician manually refines the lens
24 surface to remove surface errors identified from measurements made, for example,
25 with a laser interferometer. Other, more complex, automated methods exist such as
26 magnetorheological finishing developed by the Center for Optics Manufacturing (COM) in
27 Rochester, N.Y. However, these processes may introduce additional undesirable surface
28 errors on a lens, and generally do not achieve the nanometer and sub-nanometer
29 precision desirable in higher performance optical devices.

30 SUMMARY OF THE INVENTION

31 **[0008]** The present invention is embodied in a method of improving the shape of
32 a high-precision surface, comprising the steps of providing a block of material with a
33 feature on a surface thereof, measuring surface errors of the feature caused by
34 material that extends from the feature away from a desired feature shape, and
35 correcting the surface errors of the feature by activating a pulsed laser beam over the
36 errors to ablate the material extending from the feature.

37 **[0009]** In a further embodiment, the block of material is a mold, the feature is a

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1 cavity, and the surface errors are caused by mold material that extends into the cavity
2 away from a desired cavity shape. Alternatively, the surface errors may be tooling
3 marks from a previous mechanical processing step.

4 **[0010]** In another embodiment of the present invention, a thin film material is
5 deposited over the feature after the errors have been desirably corrected. Alternately,
6 the thin film material is deposited over the feature before the errors have been
7 measured and corrected, where measuring surface errors of the feature measures
8 surface errors caused by portions of the material extending from the thin film surface
9 and away from a desired feature shape. The pulsed laser beam is activated over the
10 errors and ablates the portions of the material extending from the thin film surface and
11 away from the desired feature shape. Alternately, a block of mold material with a
12 feature on a surface thereof and a thin film material deposited over the feature may be
13 provided without depositing the thin film material as described above.

14 **[0011]** In an alternate embodiment, an optical lens with surface errors thereon
15 caused by lens material that extends from the lens surface away from a desired lens
16 shape is provided, where the surface errors are measured and then corrected by
17 activating a pulsed laser beam over the errors to desirably ablate the lens material
18 extending from the lens surface away from a desired lens shape. In a further
19 embodiment, the lens material extending from the lens surface away from a desired
20 lens shape of the optical lens is substantially covered by a substantially optically
21 absorptive material prior to activating the pulsed laser beam over the errors.

22 **[0012]** An additional exemplary embodiment of the present invention is a laser
23 machining system for improving a shape of a high-precision surface of a device by
24 ablating device material from portions of the high-precision surface that deviate from a
25 predetermined surface design shape. This laser machining system includes: a pulsed
26 laser source for generating a pulses of laser light; a shutter aligned in a beam path of
27 the pulses of laser light; optics aligned in the beam path to focus the pulses of laser
28 light to a beam spot; a device mount to hold and controllably move the device such
29 that the beam spot is scanned over the high-precision surface of the device; and a
30 processor. Each pulse of laser light has a predetermined peak wavelength, a pulse
31 energy equal to a machining energy level, and a predetermined pulse width less than
32 about 1ns. The device mount includes: three orthogonal linear translation stages; a Θ
33 rotational stage coupled to the three orthogonal linear translation stages to rotate the
34 device about a Θ axis orthogonal to a direction of propagation of the pulses of laser
35 light at the beam spot, the Θ rotational stage allowing rotation of the device through an
36 angle of substantially 180°; a Φ rotational stage coupled to the Θ rotational stage to
37 rotate the device about a Φ axis orthogonal to the Θ axis, the Φ axis varying as the Θ

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1 rotational stage is rotated; and a holder coupled to the Φ rotational stage to hold the
2 device. The processor controls: the pulse energy of the pulses of laser light at the
3 machining energy level and the diameter of the beam spot such that each pulse of
4 laser light ablates an ablation depth of device material from the high-precision surface;
5 and the shutter and the device mount such that the portions of the high-precision
6 surface that deviate from the predetermined surface design shape are irradiated by the
7 plurality of laser pulses.

8 **[0013]** Yet another exemplary embodiment of the present invention is a multi-
9 position in situ diagnostics apparatus for use with a laser machining system. The
10 multi-position in situ diagnostics apparatus includes: a multi-position in situ
11 diagnostics shuttle; an objective lens mounted on the multi-position in situ diagnostics
12 shuttle; and a forward-facing beam alignment camera mounted on the multi-position in
13 situ diagnostics shuttle. The multi-position in situ diagnostics shuttle is arranged such
14 that: in a first shuttle position, the objective lens is aligned in a beam path of the laser
15 machining system to focus laser light of the laser machining system to a beam spot on
16 a surface; and in a second shuttle position, the forward-facing beam alignment camera
17 is aligned collinear to the beam path and images the surface of the device
18 corresponding to a location of the beam spot when the multi-position in situ diagnostics
19 shuttle is in the first position. This produces an alignment image for determining initial
20 beam alignment of the laser machining system on the surface.

21 **[0014]** Yet a further exemplary embodiment of the present invention is an
22 improved aspherical and/or asymmetric lens for use with short wavelength light. The
23 aspherical lens is formed of a lens material that includes: a first light refracting surface
24 having a first aspherical surface shape matching a predetermined first aspherical
25 surface design shape with a first surface maximum deviation of less than about $1\mu\text{m}$;
26 and a second light refracting surface opposite the first light refracting surface, the
27 second light refracting surface having a second surface shape matching a
28 predetermined second surface design shape with a second surface maximum deviation
29 of less than about $1\mu\text{m}$.

30 **[0015]** Yet an additional exemplary embodiment of the present invention is an
31 improved compression mold for short wavelength aspherical lenses, short wavelength
32 asymmetric lenses, and/or microstructures. The compression mold including a mold
33 body formed of a mold material. The mold body including a mold surface having an
34 aspherical mold surface shape that matches a predetermined aspherical surface design
35 shape with a mold surface maximum deviation of less than about $1\mu\text{m}$.

36 **[0016]** Still another exemplary embodiment of the present invention is an
37 improved release film for a compression mold. The release film includes release film

1 material formed on a mold surface of the compression mold. The release surface,
2 opposite the mold surface, of the release film material has a release surface shape
3 matching a predetermined surface design shape with a maximum deviation of less than
4 about 1 μ m.

5 **[0017]** Further embodiments of the present invention may also include the step
6 of grinding/cutting the feature on the surface of the mold, where the feature is a
7 cavity, and grinding/cutting the feature introduces cavity surface errors caused by mold
8 material that extends into the cavity away from a desired cavity shape.

9 **[0018]** It is to be understood that both the foregoing general description and the
10 following detailed description are exemplary, but are not restrictive, of the invention.

11 BRIEF DESCRIPTION OF THE DRAWING

12 **[0019]** The invention is best understood from the following detailed description
13 when read in connection with the accompanying drawing. It is emphasized that,
14 according to common practice, the various features of the drawing are not to scale. On
15 the contrary, the dimensions of the various features are arbitrarily expanded or
16 reduced for clarity. Included in the drawing are the following figures.

17 **[0020]** Figure 1A (prior art) is a cross-sectional side plan drawing of a mold with
18 a diamond grind wheel grinding a cavity therein.

19 **[0021]** Figure 1B (prior art) is a cross-sectional side plan drawing of a mold with
20 a diamond grinding wheel grinding a cavity therein.

21 **[0022]** Figure 2 (prior art) is a cross-sectional side plan drawing of a mold with a
22 diamond turning point carving a cavity therein, further illustrating exemplary causes of
23 surface cavity errors.

24 **[0023]** Figure 3A (prior art) is a cross-sectional side plan drawing of a mold with
25 a cavity formed therein.

26 **[0024]** Figure 3B (prior art) is a cross-sectional side plan drawing of the mold in
27 Figure 3A with a thin film formed thereon.

28 **[0025]** Figures 4A, 4B, and 4C are cross-sectional side plan drawings of an
29 apparatus according to an exemplary embodiment of the present invention during
30 manufacture, according to one method of the present invention.

31 **[0026]** Figures 5A, 5B, 5C, 5D, and 5E are cross-sectional side plan drawings of
32 an apparatus according to an alternate embodiment of the present invention during
33 manufacture, according to another method of the present invention.

34 **[0027]** Figure 6A is a top plan drawing of an exemplary embodiment of the
35 present invention during laser ablation of cavity surface errors.

36 **[0028]** Figure 6B is a cross-sectional side plan drawing of the exemplary
37 embodiment of the present invention during laser ablation shown in Figure 6A.

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1 **[0029]** Figure 6C is a cross-sectional side plan drawing of an alternative
2 exemplary embodiment of the present invention during laser ablation shown in Figure
3 6A.

4 **[0030]** Figure 7 is a perspective drawing of an exemplary motor-stage apparatus
5 for performing the movement steps of the present invention.

6 **[0031]** Figure 8 is a flow chart showing an exemplary method of manufacture of
7 an embodiment of the present invention.

8 **[0032]** Figure 9 is a cross-sectional side plan drawing of an alternate exemplary
9 embodiment of the present invention during laser ablation.

10 **[0033]** Figure 10 is a flow chart showing an exemplary method of manufacture
11 of an alternate embodiment of the present invention.

12 **[0034]** Figure 11 is a schematic block diagram illustrating an exemplary laser
13 machining system according to the present invention.

14 **[0035]** Figures 12A, 12B, and 12C are schematic block diagrams illustrating an
15 exemplary multi-position in situ diagnostics apparatus according to the present
16 invention.

17 **[0036]** Figure 13 is a schematic block diagram illustrating an exemplary assist
18 gas chamber according to the present invention.

19 **[0037]** Figure 14 is a side plan drawing illustrating an exemplary improved
20 aspherical lens according to the present invention.

21 **[0038]** Figure 15 is a side plan drawing illustrating an exemplary improved
22 asymmetric lens according to the present invention.

23 **[0039]** Figure 16 is a side plan drawing illustrating an exemplary improved
24 compression mold according to the present invention.

25 **[0040]** Figure 17 is a side plan drawing illustrating an alternative exemplary
26 improved compression mold according to the present invention.

27 **DETAILED DESCRIPTION OF THE INVENTION**

28 **[0041]** One embodiment of the present invention is generally directed to laser
29 ablation of undesirable features on a surface of a material to improve the shape match
30 between the actual surface shape and a desired surface shape of the high precision
31 surface of the material. These undesirable features may include such defects as tooling
32 marks caused during turning or grinding processes used to form the initial surface
33 shape. In a further embodiment, the material may be an optical mold, and the
34 features may be undesirable surface undulations in the optical mold cavity. Those
35 skilled in the art will recognize, however, that various other surfaces may be ablated
36 for higher precision using one or more of the embodiments disclosed herein without
37 departing from the present invention as defined in the claims.

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1 **[0042]** Referring now to the drawing, in which like reference numbers refer to
2 like elements throughout the various figures that comprise the drawing, Figure 4 is
3 shows an exemplary embodiment of the present invention through several stages of
4 manufacture. The step shown in Figure 4A provides a block of mold material 41. Mold
5 material 41 may generally be any hard material with desirably low thermal expansion,
6 high heat conductance, oxidation resistance, and substantially low porosity, such as
7 tungsten-carbide, a cermet (incorporating, for example, one or more of TiN, TiC, Cr₂O₃,
8 and Al₂O₃), a ceramic (for example, Al₂O₃, Cr₂O₃, SiC, ZrO₂, Si₃N₄, TiN, TiC, or BN), a
9 metal (such as Ni, Cr, Ti, W, Ta, Si, or alloy thereof), a solid state carbon material
10 (such as diamond, amorphous diamond, or glassy carbon), glass, or sapphire.

11 **[0043]** Cavity 42 is then formed on a surface of mold material 41 according to
12 one or more processes that may include, for example, the grinding/cutting process
13 described with respect to Figures 1-3, and may also include one or more of ion beam
14 milling, chemical etching, and plasma etching. Cavity 42 is desirably formed to
15 substantially correspond to desired lens shape 40, with cavity surface errors 49 formed
16 due to the imprecision of the prior art processes described above.

17 **[0044]** Figure 4B shows the mold material 41 with cavity 42 formed therein and
18 cavity surface errors 49 thereon, prior to a laser ablation process. Preceding the laser
19 ablation process, cavity surface errors 49 are detected and measured with a high-
20 precision detection device (not shown in Figure 4), which may be, for example, a laser
21 interferometer, white light interferometer, a linear variable displacement transducer, or
22 any form of scanning probe microscopy (SPM), such as a scanning tunneling
23 microscope (STM), an atomic force microscope (AFM), a near-field scanning optical
24 microscope (NSOM), or a shear-force microscope (ShFM).

25 **[0045]** Generally, these errors are mold material that undesirably extends into
26 the cavity away from a desired shape of the cavity (e.g. undulations over a desired
27 shape). The high-precision detection device may map substantially all errors 49 on the
28 surface of cavity 42. Following detection of errors 49, laser beam 45 is situated over a
29 first one of the cavity surface errors 49, whereupon a laser source (not shown) is
30 activated to provide laser beam 45 which includes at least one pulse of light and
31 desirably, a plurality of overlapping pulses, ablating the mold material extending into
32 cavity 42 away from desired lens shape 40 and thereby correcting the error. Laser
33 beam 45 is then repositioned over a further one of the cavity surface errors 49
34 according to a predetermined algorithm, whereupon which the laser source is activated,
35 desirably ablating the further error. This process is repeated until the surface of cavity
36 42 is refined to match the desired lens shape 40, as shown in Figure 4C.

37 **[0046]** The laser source used to produce laser beam 45 may be any ultrafast

1 short-pulse laser, such as a femtosecond laser or a picosecond laser. This laser source
2 may desirably include any type of solid state gain medium typically used for laser
3 machining applications, such as: Cr:YAG (peak fundamental wavelength, $\lambda_f =$
4 1520nm); Cr:Forsterite ($\lambda_f = 1230$ -1270nm); Nd:YAG and Nd:YVO₄ ($\lambda_f = 1064$ nm);
5 Nd:GdVO₄ ($\lambda_f = 1063$ nm); Nd:YLF ($\lambda_f = 1047$ nm and 1053nm); Nd:glass ($\lambda_f = 1047$ -
6 1087nm); Yb:YAG ($\lambda_f = 1030$ nm); Cr:LiSAF ($\lambda_f = 826$ -876nm); Ti:Sapphire ($\lambda_f = 760$ -
7 820nm); and Pr:YLF ($\lambda_f = 612$ nm). These solid state gain media may be pumped using
8 standard optical pumping systems such as flash lamp, erbium doped fiber lasers, and
9 diode lasers, the output pulses of which may be directly coupled into the solid state
10 gain medium or may undergo harmonic generation before being used to pump the solid
11 state gain medium. The solid state gain medium (media) may be configured to operate
12 as one or more of: a laser oscillator; a single pass amplifier; and/or a multiple pass
13 amplifier. This element also includes optics to substantially collimate the laser light.
14 The laser source may desirably produce nearly Fourier-transform limited pulses. An
15 ultrafast laser source may be desired these pulses may have a duration of less than
16 about 1ns, typically less than 50 ps. The use of an ultrafast short-pulse laser for the
17 ablation process desirably avoids thermal deformations of the mold cavity, and serves
18 to remove the undesirable undulations by stripping the electrons of the irradiated
19 atoms, essentially vaporizing the undulations with nanometer to sub-nanometer
20 precision. Alternatively, the laser source may include an excimer laser system (e.g.
21 XeCl, $\lambda_f = 308$ nm; KrF, $\lambda_f = 248$ nm; ArF, $\lambda_f = 193$ nm; or F₂, $\lambda_f = 157$ nm), a dye laser
22 system (e.g. 7-diethylamino-4-methylcoumarin, $\lambda_f = 435$ -500nm; benzoic acid, 2-[6-
23 (ethylamino)-3-(ethylimino)-2,7-dimethyl-3H-xanthen-9-yl]-ethyl ester,
24 monohydrochloride, $\lambda_f = 555$ -625nm; 4-dicyanmethylene-2-methyl-6-(p-
25 dimethylaminostyryl)-4H -pyran, $\lambda_f = 598$ -710nm; or 2-(6-(4-dimethylaminophenyl)-
26 2,4-neopentylene-1,3,5-hexatrienyl)-3-methylbenzothiazolium perchlorate, $\lambda_f = 785$ -
27 900nm), or other laser system used in laser machining applications.

28 **[0047]** In order to prevent undesirable oxidation of the cavity surface, the laser
29 ablation process may be performed in an inert atmosphere. This inert atmosphere is
30 selected to reduce the likelihood of oxidation of the mold surface during the laser
31 ablation process and may include N₂ or a noble gas such as Ar. Alternatively, an assist
32 gas such as: N₂, Ar, O₂, air, CF₄, Cl, H₂, or SF₆, may be used to assist in the ablation
33 process by forming a plasma during laser illumination.

34 **[0048]** Prior to the ablation process described above, the laser may be calibrated
35 for a particular material. The calibration process may include the steps of providing a
36 block of the material, focusing the laser on a surface of the block of material, applying
37 a pulse of light with a predetermined minimum power, and stepping up the power of

1 the pulse of light until the surface of the material is desirably ablated to a certain depth
2 (i.e., finding the ablation threshold). The ablation threshold power obtained in the
3 calibration process may then be used in the ablation process of the present invention.
4 In an exemplary embodiment, pulses having a power slightly greater than the ablation
5 threshold are used to remove unwanted material from the mold.

6 **[0049]** The mold material 41 with cavity 42 substantially matching, for example,
7 lens shape 40 described above, may be further processed to include a thin film material
8 over cavity 42. As described above, with respect to Figure 3, thin film 33 is desirably
9 formed over the surface of at least the cavity 32 in order to prevent bonding of lens
10 material (not shown in Figure 3) to mold 31 in a mold pressing process for fabrication
11 of an optical lens. As described above, thin film deposition according to the prior art
12 may present undesirable thin film surface errors and undulations (not shown in Figure
13 3), which may augment the underlying cavity surface errors, thereby presenting even
14 larger surface undulations on the thin film surface. The application of thin film
15 according to the present invention, however, may preclude the formation of such errors
16 and undulations due to the improved shape accuracy of the laser processed mold cavity
17 surface underlying the thin film.

18 **[0050]** In a further embodiment of the present invention, the thin film may be
19 formed from a metal or alloy containing one or more of nickel, titanium, niobium,
20 vanadium, molybdenum, platinum, palladium, iridium, rhodium, osmium, ruthenium,
21 rhenium, tungsten, and tantalum, for example. Furthermore, the thin film may be
22 applied using physical vapor deposition (PVD), chemical vapor deposition (CVD),
23 molecular beam epitaxy (MBE), ion beam deposition, or electroplating. Generally, it is
24 desirable that a thin film having predetermined thickness be applied to match features
25 of the underlying surface, thereby matching a desired lens shape. In one embodiment,
26 the predetermined thin film thickness may range from 1 to 5 microns, for example.
27 Those skilled in the art will recognize that alternate thin film materials may be used for
28 each particular application, depending on the optical lens material that is to be molded
29 in that application. Alternately, the thin film may not be required, and may thus be
30 omitted.

31 **[0051]** Figure 5 shows an alternate embodiment of the present invention, in
32 which the thin film is applied prior to the laser ablation process. In this embodiment,
33 mold material 41 including cavity 42 with cavity surface errors 49 thereon is provided
34 and a thin film of release material 53 is formed over at least a surface of the cavity 42.
35 Thin film 53 may be formed using one or more of the processes described above.
36 Inherent in the formation of thin film 53 is the formation of thin film cavity 52, having
37 one or more thin film surface errors 59. Generally, these errors are caused by release

1 material that undesirably extends into the thin film cavity away from a desired shape of
2 the cavity (e.g. undulations over the desired concave shape). Thin film surface errors
3 59 may be formed due to the presence of cavity surface errors 49 underlying thin film
4 53, manufacturing imprecision, or any number of environmental conditions. It can be
5 seen that the resulting thin film cavity 52 does not desirably conform to desired lens
6 design 50.

7 **[0052]** Prior to correction of errors 59 in the thin film release layer 53, errors 59
8 may be detected and measured with a high-precision detection device (not shown in
9 Figure 5), which may be, for example, a laser interferometer, white light
10 interferometer, a linear variable displacement transducer, or any form of scanning
11 probe microscopy (SPM), such as a scanning tunneling microscope (STM), an atomic
12 force microscope (AFM), a near-field scanning optical microscope (NSOM), or a shear-
13 force microscope (ShFM). The high-precision detection device desirably may map
14 substantially all errors 59 on the surface of thin film cavity 52. Following detection of
15 errors 59, laser beam 55 is desirably situated over a first one of the thin film surface
16 errors 59, whereupon which a laser source (not shown) is activated to produce laser
17 beam 55 by releasing at least one pulse of light and, desirably, a plurality of
18 overlapping pulses, ablating the release material extending into cavity 52 away from
19 desired lens design 50 and thereby correcting the error. Laser beam 55 is then
20 repositioned over a further one of the cavity surface errors 59 according to a
21 predetermined algorithm, whereupon the laser source is activated, such that laser
22 beam 55 may desirably ablate the further error. This process is repeated until thin film
23 cavity 52 is refined to substantially remove identified surface errors, thereby matching
24 cavity 52 to desired lens design 50, as shown in Figure 5E. As described above, the
25 laser source may generally be any ultrafast short-pulse laser, such as a femtosecond
26 laser or a picosecond laser.

27 **[0053]** Figure 6 illustrates a further embodiment of the present invention, where
28 laser beam 65 is adjusted relative to the surface of mold cavity 42 such that a
29 substantially normal angle of incidence is maintained as the surface of mold cavity 42 is
30 moved according to an exemplary path algorithm 66 to desirably correct cavity surface
31 errors 49 along its path. Alternately, laser beam 65 may generally be held at any
32 desirable angle of incidence to the surface of mold cavity 42 as it is moved along its
33 path. For example, laser beam 65 may be directed parallel to axis of rotation 60 of
34 mold 41, as shown in Figure 6C. In the exemplary embodiment illustrated in Figure
35 6C, the polarization of laser beam 65 may be varied to reduce the potential of
36 increasing surface roughness during the laser processing of the surface due to
37 stimulated Woods anomalies.

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1 **[0054]** Figure 6A illustrates a top plan drawing of mold cavity 42 (shown as a
2 declining gradient) with laser beam 65 (shown as a beam spot) moving along laser
3 path 64, according to an exemplary path algorithm 66. Laser path 64 illustrates
4 movement of the laser with progressively transparent phantom images of the beam
5 spots of laser beam 65 along increasingly earlier points of its path in time. The
6 progressively transparent phantom images of laser beam 65 may also indicate a
7 desirable number of overlapping short-pulse beam emissions upon the mold cavity
8 surface on any point along laser path 64. As illustrated in Figure 6A, the laser may be
9 swept in a desired path, wherein the laser is operated to emit short-pulses with a bite
10 (circumferential distance between pulses) such that a desirable overlapping of regions
11 ablated by consecutive pulses along the desired portion of the path occurs. The bite is
12 typically selected to be less than or equal to $1/2$ of the width of the region ablated by
13 each pulse, desirably less than or equal to $1/3$ of the width, or preferably less than or
14 equal to $1/10$ of the width.

15 **[0055]** In one embodiment of the invention, mold cavity 42 is substantially
16 circularly symmetric, and laser beam 65 may be used to desirably correct errors in
17 mold cavity 42 to substantially attain desired shape 40. It is noted that the errors in
18 the surface shape may often be substantially circularly symmetric, particularly if the
19 errors are tooling marks caused by either grinding or cutting the mold cavity. These
20 tooling marks typically follow a spiral path with rings that are closely packed enough to
21 approximate concentric circles. Therefore, correction of these errors may be
22 accomplished by moving a beam spot of the laser beam 65 along a perimeter of the
23 substantially circularly symmetric mold cavity 42 in one of a clockwise direction or a
24 counterclockwise direction (such as along ablation path 64, for example) at a
25 predetermined rate of spin. A laser source (not shown) may then be activated at a
26 predetermined frequency to apply pulses of light as laser beam 65 along the perimeter
27 of the cavity, wherein centers of ablated regions from consecutively applied pulses are
28 separated by a predetermined circumferential distance. The predetermined
29 circumferential distance is typically less than the diameter of the region ablated by
30 laser beam 65 and may be $1/2$ of the diameter of the ablation region or less for each
31 pulse, for example. This ablation process may be repeated at the current perimeter of
32 the mold cavity until the errors along the perimeter of the substantially circularly
33 symmetric mold cavity are corrected. Then, either the mold or the beam spot of the
34 laser may be moved radially by a predetermined radial distance to cause the beam spot
35 to move around a new perimeter of the substantially circularly symmetric mold cavity.
36 This new perimeter may be either a smaller perimeter or a larger perimeter. This

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1 process may be repeated until the errors in the mold cavity are desirably ablated.

2 **[0056]** In a further embodiment of the invention, the predetermined frequency
3 of activating the laser source may be varied to a predetermined value for each
4 perimeter in order to cause the predetermined circumferential distance between the
5 centers of the ablated regions from consecutively applied pulses to remain substantially
6 constant for each of the various perimeters. Alternately, the predetermined rate of
7 spin of either the mold or the beam spot may be varied to a predetermined value for
8 each perimeter in order to cause the predetermined circumferential distance between
9 the centers of the ablated regions from consecutively applied pulses to remain
10 substantially constant for each of the various perimeters.

11 **[0057]** In one embodiment of the present invention, exemplary path algorithm
12 66 dictates movement of laser beam 65 in the refining of the mold cavity surface
13 shape. The exemplary path algorithm 66 shown in Figure 6A, for example, moves laser
14 beam 65 counterclockwise along an outer perimeter of the mold cavity. After at least
15 one counterclockwise sweep, laser beam 65 is stepped downward to a closer perimeter
16 of the mold cavity (i.e., closer to the center of the mold cavity) and the
17 counterclockwise sweeping process is performed again. During the counterclockwise
18 sweeps, laser beam 65 is selectively activated over cavity surface errors to desirably
19 ablate the undulations, thereby correcting the errors. The process is repeated as
20 necessary to desirably improve the surface shape of the mold cavity. In an alternate
21 embodiment, the process described above may be performed with respect to a thin film
22 cavity surface (not shown in Figure 6) of a thin film applied over at least a surface of
23 the mold cavity.

24 **[0058]** Figure 7 shows an exemplary motor apparatus 700 for carrying out the
25 laser ablation algorithm of one embodiment of the present invention. Stages x-shift
26 702, y-shift 704, and z-shift 706 are brushless, coreless linear motor stages for moving
27 optical mold 712 held by rotary-shift 708 to a desired location with respect to laser
28 beam 710. Laser beam 710 may be aligned at an arbitrary Φ angle in the cylindrical
29 coordinate system having z as its radial axis. In one embodiment, Φ may be set to any
30 angle between nearly $+90^\circ$ and -90° . In another embodiment, Φ may be dynamically
31 altered throughout the ablation process so as to maintain a desirable alignment
32 between laser beam 710 and the surface of mold 712.

33 **[0059]** The laser ablation process may begin once laser beam 710 and mold 712
34 are situated with respect to one another such that the surface of mold 712 is located at
35 a distance substantially equal to the focus of laser beam 710. Rotary-shift 708
36 desirably rotates mold 712 at a predetermined rotational rate. As mold 712 is being
37 rotated, laser 710 is selectively activated to pulse the surface of mold 712 such that

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1 the overlapping pulses ablate errors on the surface of mold 712. The pulse schedule is
2 determined based on an average ablation per pulse figure and the size and location of
3 undulations on the surface of mold 712, which are previously identified using a high-
4 precision detection device. In one embodiment, a layer of approximately .1nm - 10 nm
5 thickness of the surface is ablated by each pulse. As seen in Figure 7, laser 710 may be
6 positioned to apply pulses along a circular path with a certain radius from the center of
7 the surface of mold 712. Once the surface errors have been ablated along this initial
8 path, motor stage apparatus 700 may move mold 712 so that laser 712 now applies
9 pulses along a circular path with a different radius from the center. Alternately, laser
10 710 may be moved to apply pulses at a different circular path radius. The process may
11 be iterated until undulations on the surface of mold 712 have been desirably removed
12 or minimized.

13 **[0060]** While the embodiments of the present invention as illustrated in the
14 drawings show the mold and lens as being substantially horizontal, those skilled in the
15 art will recognize that this is not a requirement of the invention. Generally, the mold or
16 lens may be held at arbitrary θ and Φ angles in a cylindrical coordinate system.
17 Further, they may be positioned to be substantially vertical so that debris ejected from
18 the mold during the ablation process may fall away from the mold surface. Additionally,
19 a jet of air may be blown across the mold such that debris is pushed away from the
20 mold surface during ablation.

21 **[0061]** In one embodiment of the invention, the laser ablation process may take
22 place in the presence of an assist gas, and/or while an assist gas is being blown over
23 the surface of the mold cavity. In such an embodiment, selectively activating the laser
24 as the laser beam passes over the undulations may apply pulses of light that chemically
25 activate the assist gas over the undulations, thereby improving ablation of the errors in
26 mold cavity. In further embodiments, this chemically activated ablation may correct
27 errors on a surface of a thin film or lens. The assist gas may include at least one of N_2 ,
28 Ar, O_2 , air, CF_4 , Cl, H_2 , or SF_6 , for example.

29 **[0062]** Figure 8 is a flow chart showing several exemplary methods of
30 manufacture of an exemplary embodiment of the present invention. The exemplary
31 alternative methods are illustrated using phantom process blocks and alternative
32 process blocks in the flow chart. An actual assembly method would use one of the
33 respective paths, without any decision blocks.

34 **[0063]** An exemplary process may begin in one of three ways as illustrated by
35 steps 800a, 800b, and 800c, described below. Step 800a provides a block of mold
36 material, into which a cavity is formed in step 802a. The cavity is formed so that it
37 substantially matches a desired lens shape. Step 800b, however, provides a block of

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1 mold material that already contains a cavity, thereby bypassing step 802a. In step
2 804a, a thin film may be formed over at least the cavity. This process is shown in
3 phantom, as it may be omitted or performed subsequent to a "NO" condition at step
4 816 (not shown in Figure 8). An alternate start step 800c provides a block of mold
5 material that already contains a cavity and a thin film formed over the cavity.

6 **[0064]** Step 810 proceeds to detect and measure surface errors on a surface of
7 the thin film or cavity, depending on which path is taken in previous steps. If a path is
8 taken so that a thin film has been formed over the cavity, then step 810 detects and
9 measures surface errors on the surface of the thin film. Whereas, if a path is taken so
10 that no thin film has been formed over the cavity, step 810 detects and measures
11 surface errors directly on a surface of the cavity. The errors being detected in step 810
12 generally represent undulations on a surface of the thin film or mold cavity signifying
13 deviations from a desired lens design. Step 810 may also include steps to identify and
14 partition the errors (for example, into a histogram or surface map of the cavity), listing
15 the errors by their location and shape, and defining a desired pattern of laser pulses to
16 correct each error.

17 **[0065]** Once step 810 has mapped errors on the surface of the thin film or mold
18 cavity, step 812 positions the laser over a first identified error, which is designated as a
19 current error. In this example, a surface error may be one or more adjacent
20 undulations on a material surface that have a minimal path gap in between them. Step
21 814 activates the laser to emit at least one short pulse beam of light that desirably
22 corrects the current error by ablating the undulation causing the error. Generally,
23 individual pulses may be applied, with multiple pulses being applied to ablate the
24 surface error to a desired depth. Furthermore, as illustrated in Figure 6A, the activation
25 of the laser to emit at least one short pulse may be done in conjunction with moving
26 the laser along a predetermined path pursuant to a predetermined algorithm so that,
27 for example, selectively generated pulses may overlap in groups of 10 or more to
28 ablate the surface errors. Step 816 determines whether any further errors remain on
29 the surface of the thin film or mold cavity. If further errors exist, a next error is
30 designated as the current error, and control transfers back to step 812, which positions
31 the laser over the current error. Step 814 desirably ablates the current error,
32 transferring control to step 816. This process is repeated until no further errors remain
33 on the thin film or mold cavity, transferring control to a "DONE" condition 888, thereby
34 signifying that the desirably high-precision, laser-refined mold has been completed. In
35 a further embodiment, steps 812, 814, and 816 may be encompassed by step 810. In
36 step 810, a complete laser ablation process may be defined by an algorithm including
37 information on the number of pulses required to correct each surface error, the precise

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1 locations of those errors, and a predetermined algorithm developed to efficiently
2 remove the errors. The predetermined algorithm may be a laser movement schedule
3 that moves the laser relative to the mold from a first error to a final error in a minimal
4 number of moves and desirably corrects each surface error with 1 to 10 or more
5 overlapping pulses of light. In an alternate embodiment, the predetermined algorithm
6 may be a laser pulse schedule, where the optical mold is rotated according to the
7 description with respect to Figure 7, and the ultrafast laser is activated on a pulse
8 schedule so as to desirably ablate the errors.

9 **[0066]** If step 804a was not taken to form a thin film over the mold cavity, then
10 this process may be performed once refining of the mold cavity is completed and
11 control has transferred to the step 888. In a further embodiment, it may be desirable
12 to execute the above process from step 810 for a high-precision, laser-corrected mold,
13 where a thin film is formed over the mold cavity, and steps 810-816 desirably ablate
14 any errors introduced by the formation of the thin film.

15 **[0067]** In an alternate embodiment of the present invention, shown in Figure 9,
16 an optical lens 91 is provided. Optical lens 91 is formed according to a prior art
17 process, and therefore has undesirable deviations from desired lens shape 90, the
18 deviations being lens material extending from the surface of optical lens 91 away from
19 desired lens shape 90. In the exemplary embodiment, a laser source (not shown) may
20 be activated over one or more deviations from the desired lens shape 90 to produce
21 laser beam 95 and ablate the lens material extending from the surface of optical lens
22 91 away from desired lens shape 90, thereby correcting the deviations and refining
23 optical lens 91 to conform to desired lens shape 90. It may also be desirable to coat
24 optical lens 91 with a substantially light absorptive temporary coating (not shown in
25 Figure 9) over at least the deviations thereon, where the light absorptive coating may
26 desirably increase absorption of a pulsed beam from laser beam 95.

27 **[0068]** Figure 10 is a flow chart showing an exemplary method of manufacture
28 of an alternate embodiment of the present invention. In the present embodiment, an
29 optical lens is directly refined using the laser ablation process described above, to
30 desirably remove surface errors representing deviations from a desired lens shape.
31 Step 900 provides an optical lens. Step 910 then detects and measures surface errors
32 on the optical lens, where the surface errors may be undulations presenting
33 undesirable deviations from a desired lens shape. Although not necessary, during this
34 step, the optical lens surface errors may be coated with a substantially optically
35 absorptive temporary film that may serve to desirably increase absorption of the laser
36 beam used in the ablation process.

37 **[0069]** Once step 910 has mapped out errors on the surface of the optical lens,

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1 step 912 positions the laser over a first identified error, which is designated as a
2 current error. Step 914 activates the laser to emit a short pulse beam of light that
3 desirably ablates the current error. The laser activation step may generally be the same
4 as that in step 814. Step 916 determines whether any further errors remain on the
5 surface of the optical lens. If further errors exist, a next error is designated as the
6 current error, and control transfers back to step 912, which positions the laser over the
7 current error. Step 914 desirably ablates the current error, transferring control to step
8 916. This process is repeated until no further errors remain on the surface of the
9 optical lens, transferring control to a "DONE" condition 999, thereby signifying that the
10 high-precision, laser-refined optical lens has been completed. In a further embodiment,
11 steps 912, 914, and 916 may be encompassed by step 910. In step 910, a complete
12 laser ablation process may be defined by an algorithm including information on the
13 number of pulses required to correct each surface error, the precise locations of those
14 errors, and a predetermined algorithm to desirably ablate the errors. The
15 predetermined algorithm may be a laser movement schedule that moves the laser from
16 a first error to a final error in a minimal number of moves and desirably corrects each
17 surface error with 1 to 10 or more overlapping pulses of light. In an alternate
18 embodiment, the predetermined algorithm may be a laser pulse schedule, where the
19 optical mold is rotated according to the description with respect to Figure 7, and the
20 ultrafast laser is activated on a determined pulse schedule so as to desirably ablate the
21 errors.

22 **[0070]** Figure 11 illustrates a block diagram of an exemplary laser machining
23 system that may be used with the exemplary methods of the present invention to
24 improving the shape of a high-precision surface of device 1128. This exemplary
25 system may desirably improve the surface shape by ablating device material from
26 portions of the high-precision surface that deviate from a predetermined surface design
27 shape.

28 **[0071]** This system includes pulsed laser source 1100 for generating a plurality
29 of pulses of laser light that may be transmitted along beam path 1101. Laser source
30 1100 may be any ultrafast short-pulse laser, such as a femtosecond laser or a
31 picosecond laser. This laser source may desirably include any type of solid state gain
32 medium typically used for laser machining applications, such as: Cr:YAG (peak
33 fundamental wavelength, $\lambda_f = 1520\text{nm}$); Cr:Forsterite ($\lambda_f = 1230\text{-}1270\text{nm}$); Nd:YAG
34 and Nd:YVO4 ($\lambda_f = 1064\text{nm}$); Nd:GdVO4 ($\lambda_f = 1063\text{nm}$); Nd:YLF ($\lambda_f = 1047\text{nm}$ and
35 1053nm); Nd:glass ($\lambda_f = 1047\text{-}1087\text{nm}$); Yb:YAG ($\lambda_f = 1030\text{nm}$); Cr:LISAF ($\lambda_f = 826\text{-}$
36 876nm); Ti:Sapphire ($\lambda_f = 760\text{-}820\text{nm}$); and Pr:YLF ($\lambda_f = 612\text{nm}$). These solid state
37 gain media may be pumped using standard optical pumping systems such as flash

1 lamp, erbium doped fiber lasers, and diode lasers, the output pulses of which may be
2 directly coupled into the solid state gain medium or may undergo harmonic generation
3 before being used to pump the solid state gain medium. The solid state gain medium
4 (media) may be configured to operate as one or more of: a laser oscillator; a single
5 pass amplifier; and/or a multiple pass amplifier. This element also includes optics to
6 substantially collimate the laser light.

7 **[0072]** Laser source 1100 may desirably produce nearly Fourier-transform
8 limited pulses. An ultrafast laser source may be desired to produce pulses having a
9 duration of, for example, less than about 1ns, typically less than about 50 ps. The use
10 of an ultrafast short-pulse laser for the ablation process desirably avoids thermal
11 deformations of the mold cavity, and serves to remove the undesirable undulations by
12 stripping the electrons of the irradiated atoms, essentially vaporizing the undulations
13 with nanometer to sub-nanometer precision.

14 **[0073]** Alternatively, laser source 1100 may include an excimer laser system
15 (e.g. XeCl, $\lambda_f = 308\text{nm}$; KrF, $\lambda_f = 248\text{nm}$; ArF, $\lambda_f = 193\text{nm}$; or F_2 , $\lambda_f = 157\text{nm}$), a dye
16 laser system (e.g. 7-diethylamino-4-methylcoumarin, $\lambda_f = 435\text{-}500\text{nm}$; benzoic acid, 2-
17 [6-(ethylamino)-3-(ethylimino)-2,7-dimethyl-3H-xanthen-9-yl]-ethyl ester,
18 monohydrochloride, $\lambda_f = 555\text{-}625\text{nm}$; 4-dicyanmethylene-2-methyl-6-(p-
19 dimethylaminostyryl)-4H -pyran, $\lambda_f = 598\text{-}710\text{nm}$; or 2-(6-(4-dimethylaminophenyl)-
20 2,4-neopentylene-1,3,5-hexatrienyl)-3-methylbenzothiazolium perchlorate, $\lambda_f = 785\text{-}$
21 900nm), or other laser system used in laser machining applications.

22 **[0074]** Each pulse of laser light desirably has a predetermined peak wavelength.
23 This peak wavelength is dependent on the gain medium of the laser oscillator used in
24 laser source 1100. Additionally, laser oscillator 1100 may produce initial pulses of laser
25 light having a fundamental peak wavelength, which is longer than the predetermined
26 peak wavelength. Harmonic generation crystal 1102 may be included to generate
27 pulses of laser light having the predetermined peak wavelength from the initial pulses
28 of laser light generated by the laser oscillator.

29 **[0075]** Each pulse of laser light also desirably has a pulse energy equal to or
30 slightly greater than a machining energy level. This machining energy level may be
31 dependent on a number of factors, such as the beam spot size on the high-precision
32 surface to be machined and the depth of material desired to be ablated with each
33 pulse. It is noted that the desired pulse energy of the pulses may vary during the
34 machining process. Although the pulse energy of pulses generated by laser source
35 1100 may be directly adjusted, this may lead to undesirable shifts in the peak
36 wavelength, pulse width, or other parameter associated with the laser pulses.
37 Therefore, to allow control of the pulse energy, it may be desirable to have a pulsed

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1 laser oscillator that produces the pulses of laser light having a predetermined initial
2 pulse energy, which is equal to the maximum desired pulse energy. The pulse energy
3 of these initial pulses may then be controlled by variable attenuator 1106, which is
4 coupled to processor 1130 to control the pulse energy of the pulses of laser light, even
5 as the machining energy level varies.

6 **[0076]** Variable attenuator 1106 desirably allows for fine control of the pulse
7 energies, and thus the beam fluence. Variable attenuator 1106 is desirably a
8 polarization type of controllable variable attenuator that may withstand the high peak
9 powers associated with ultrafast lasers. For example a pair of linear polarizing
10 members arranged on either side of a controllable polarization rotation element such as
11 a Pockels cell, Kerr cell, or a liquid crystal. Alternatively, a fixed linear polarizing
12 member and a rotatable polarization member may be used as variable attenuator
13 1106.

14 **[0077]** The pulses of laser light are desirably generated by pulsed laser source
15 1100 with a constant repetition rate. The higher the repetition rate the more quickly
16 the laser machining system may operate, but this also increases the duty cycle and
17 heat dissipation of laser source 1100 and other system components as well. The
18 repetition rate is desirably at least about 1kHz, though a higher repetition rate of
19 20kHz or more is contemplated.

20 **[0078]** Although laser source 1100 desirably operates at constant repetition
21 rate, it may be desirable for the high-precision surface to be machined at a non-
22 constant rate. Therefore, shutter 1104 is aligned in beam path 1101 of the pulses of
23 laser light. Desirably, shutter 1104 may include a mechanical shutter to allow the
24 beam to be blocked 1) during realignments of device 1128 to allow other portions of
25 the high-precision surface to be machine or 2) while device 1128 is removed and a new
26 device mounted on five-axis device mount 1122. It is noted that a mechanical chopper
27 may be used to reduce the number of pulses transmitted through shutter 1104 to
28 irradiate the high-precision surface of device 1128.

29 **[0079]** Alternatively, shutter 1104 may include a high speed electro-optical
30 pulse picker. Such a pulse picker may desirably have a switching time less than the
31 inverse of the repetition rate of the pulses of laser light generated by laser source
32 1100. A switching time of this duration may allow individual pulses from the plurality
33 of pulses generated by laser source 1100 to be selectively transmitted or blocked by
34 shutter 1104. This selective transmission of pulses by shutter 1104 may be
35 responsive to signals from processor 1130. These pulse picking signals may be
36 generated by processor 1130 based on the position of the beam spot on the high-
37 precision surface as monitored by sensors in five axis device mount 1122. The

1 operation of these sensors is described below in detail.

2 **[0080]** The high speed electro-optical pulse picker may be based on one of a
3 number of electro-optical devices, including: a Pockels cell; a Mach-Zehnder
4 interferometer; a Kerr cell; a liquid crystal; or an electroabsorption cell. The high peak
5 power of ultrafast laser pulses may pose problems for many of these devices, leading
6 to difficulties, such as high current densities in an electroabsorption cell based pulse
7 picker and excessive heating in a liquid crystal based pulse picker. These exemplary
8 difficulties may be overcome by enlarging the electroabsorption cell or using multiple
9 polarizing layers to absorb the pulse energy. The potential need for rapid switching
10 between a transmission state and a blocking state may cause additional difficulties for
11 these exemplary high speed electro-optical pulse picker, particularly for picking pulses
12 from high repetition rate ($<20\text{kHz}$) laser sources. High speed circuitry, having a low
13 inductance and possibly involving the use of a number of capacitors that may be
14 charged and discharged sequentially, may be used to provide the electrical signals
15 necessary to operate these exemplary high speed electro-optical pulse pickers.

16 **[0081]** While such a high speed electro-optical pulse picker may be used to
17 transmit arbitrary pulse trains from the periodic pulses generated by the laser source,
18 it may be desirable to use a high speed electro-optical pulse picker to selectively
19 transmit every n^{th} pulse, where n is a positive integer, while blocking the other pulses.
20 This creates an effective repetition rate of pulses of laser light irradiating the high-
21 precision surface, which is equal to the repetition rate of the laser source divided by n .
22 For example, this may be particularly desirable for machining circularly symmetric
23 surfaces, where lower repetition rates may be desirable as the beam spot scans rings
24 with shorter radii. As describe above, it may be desirable for the scan rate of the beam
25 spot over the high-precision surface to be less than one half of the diameter of the
26 beam spot times the effective repetition rate with which pulses of laser light irradiate
27 the high-precision surface, or preferably less than one tenth of the beam spot diameter
28 times the effective repetition rate, but slower scan speeds may lead to excessive
29 ablation from irradiating the same location too many times. Thus, near the center of a
30 circular symmetric surface, circular scans may require unreasonable high rotational
31 speeds, unless the repetition rate is lowered. Processor 1130 may be used to control
32 the high speed electro-optical pulse picker to match the repetition rate to the radial
33 distance from the center of the circularly symmetric high precision surface, so that the
34 rotational speed of spindle 1124 may be maintained in a desired range. Another
35 method avoid over ablation near the center of a circularly symmetric high precision
36 surface is for processor 1130 control the diameter of the beam spot such that the scan
37 rate of the beam spot over the high-precision surface is less than one half of the

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1 diameter of the beam spot times the effective repetition rate with which pulses of laser
2 light irradiate the high-precision surface. The diameter of the beam spot may be
3 controlled by adjusting objective lens 1120 or by using five axis device mount 1122 to
4 move device 1128 to different focal positions of objective lens 1120.

5 **[0082]** The exemplary laser machining system of Figure 11 may also include
6 polarization control means 1110 aligned in the beam path to control a polarization of
7 the plurality of pulses of laser light. Polarization control means may desirably control
8 the polarization of the pulses of laser light such that the pulses are substantially
9 circularly polarized in the beam spot, or may allow for control of the polarization to
10 allow various elliptic polarizations.

11 **[0083]** It is noted that variable attenuator 1106 desirably produces laser light
12 linearly polarized in a known direction. This is because linearly polarized light is
13 desirable as the input light for polarization control means 1110, which may, for
14 example, include a quarter wave plate (possibly rotatable) and may include a linear
15 polarization rotator as well. Although this exemplary polarization control means uses
16 linearly polarized input light, it may be understood by one skilled in the art that input
17 light having other polarizations may be used, as long as the polarization of the input
18 light is known, with minor changes to the elements of polarization control system. It is
19 also noted that a fixed linear polarizer (not shown) may be added.

20 **[0084]** A linear polarization rotator, such as a controllable polarization rotation
21 element that functions as a rotatable half wave plate, may be used to controllably
22 rotate the polarization direction of the laser pulses transmitted by variable attenuator
23 1106 to a desired angle. This linear polarization rotator may desirable be a half wave
24 plate that may be physically rotated or may be an electro-optical device, such as a
25 Pockels cell, a Kerr cell, or a liquid crystal that may rotate the polarization direction of
26 light a controlled amount based on an applied electric field. A rotatable quarter wave
27 plate may then transform the polarization of the pulses of laser light to have an
28 elliptical polarization. Alternatively, a stationary quarter wave plate may be used alone
29 to transform the polarization of the pulses of laser light to a circular polarization.

30 **[0085]** Various optics, such as steering mirrors 1108 and 1118 and objective
31 lens 1120 are aligned in the beam path to direct and focus the pulses of laser light to a
32 beam spot on the high-precision surface of device 1128. Objective lens 1120 may be
33 part of exemplary multi-position in situ diagnostics apparatus 1200 illustrated in
34 Figures 12A, 12B, and 12C.

35 **[0086]** Exemplary multi-position in situ diagnostics apparatus 1200 includes
36 multi-position in situ diagnostics shuttle 1202 with objective lens 1120, forward-facing
37 beam alignment camera 1204, and backward-facing beam quality camera 1206

1 mounted on multi-position in situ diagnostics shuttle 1202. Forward-facing beam
2 alignment camera 1204 is desirably a CCD camera having adequate resolution to image
3 features ablated on the high-precision surface by the pulses of laser light, and
4 backward-facing beam quality camera 1206 is desirably a CCD camera capable of
5 providing cross-sectional images of the spatial mode structure of the pulses.
6 Backward-facing beam quality camera 1206 may include a narrow band filter to
7 improve the quality of its spatial mode structure images.

8 **[0087]** In situ diagnostics shuttle 1202 may desirably be a linear motion stage
9 designed to repeatably stop at specific positions. Figures 12A, 12B, and 12C illustrate
10 exemplary multi-position in situ diagnostics apparatus 1200 in its three positions, i.e.
11 the first shuttle position (Figure 12A), the second shuttle position (Figure 12B), and the
12 third shuttle position (Figure 12C). Each of the three components mounted on in situ
13 diagnostics shuttle 1202 may be brought into alignment with beam path 1101 in one of
14 these positions.

15 **[0088]** Figure 12A illustrates in situ diagnostics shuttle 1202 in the first shuttle
16 position, in which objective lens 1120 is aligned in beam path 1101 to focus the
17 plurality of pulses of laser light to the beam spot.

18 **[0089]** Figure 12B illustrates in situ diagnostics shuttle 1202 in the second
19 shuttle position, in which forward-facing beam alignment camera 1204 is aligned
20 collinear to beam path 1101 so that it may image reflected light 1208 from an ablated
21 area on the high precision surface of the device corresponding to the location of the
22 beam spot when the multi-position in situ diagnostics shuttle is in the first position.
23 This allows forward-facing beam alignment camera 1204 to produce an alignment
24 image that matches the area to be irradiated. Processor 1130 may then determine the
25 initial beam alignment based on this alignment image. This alignment information
26 allows processor 1130 to control shutter 1104 and five axis device mount 1122 to
27 select specific areas of the high-precision surface to irradiate with laser pulses. It is
28 noted that it may not be desirable for pulses to be transmitted along beam path 1101
29 when situ diagnostics shuttle 1202 is in the second shuttle position. A beam stop (not
30 shown) may be provided on situ diagnostics shuttle 1202 opposite forward-facing beam
31 alignment camera 1204 to prevent damage to forward-facing beam alignment camera
32 1204 if pulses are transmitted along beam path 1101 when situ diagnostics shuttle
33 1202 is in the second shuttle position.

34 **[0090]** Figure 12C illustrates in situ diagnostics shuttle 1202 in the third shuttle
35 position, in which backward-facing beam quality camera 1206 is aligned collinear to
36 beam path 1101 to image a cross-section of the pulses of laser light that may be used
37 to determine beam quality.

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1 **[0091]** It is noted that objective lens 1120, forward-facing beam alignment
2 camera 1204, and backward-facing beam quality camera 1206 may desirably be
3 mounted in a row on multi-position in situ diagnostics shuttle 1202 along a shuttle
4 translation line, as shown in Figures 12A, 12B, and 12C. In this exemplary
5 embodiment, multi-position in situ diagnostics shuttle 1202 moves between the shuttle
6 positions by translating along the shuttle translation line. Desirably, the shuttle
7 translation line is aligned substantially perpendicular to beam path 1101 and
8 substantially parallel to the Θ axis of Θ rotational stage 1126 of device mount 1120, as
9 shown in Figure 11. This orientation allows Θ rotational stage 1126 the greatest range
10 of motion without being obstructed by multi-position in situ diagnostics shuttle 1202.
11 Alternatively they may be mounted at in a circular arc and rotated into position.

12 **[0092]** It is also contemplated that multi-position in situ diagnostics apparatus
13 1200 may include: an XY lens translation stage (not shown), coupling objective lens
14 1120 to in situ diagnostics shuttle 1202, to align the axis of beam path 1101 with the
15 center of objective lens 1120 when in the first shuttle position; an XY camera
16 translation stage (not shown), coupling forward-facing beam alignment camera 1204 to
17 in situ diagnostics shuttle 1202, to align the axis of beam path 1101 with the center of
18 forward-facing beam alignment camera 1204 when in the second shuttle position; and
19 an XY camera translation stage (not shown), coupling backward-facing beam quality
20 camera 1206 to in situ diagnostics shuttle 1202, to align the axis of beam path 1101
21 with the center of backward-facing beam quality camera 1206 when in the third shuttle
22 position.

23 **[0093]** The exemplary laser machining system of Figure 11 also includes five
24 axis device mount 1122 to hold and controllably move device 1128 such that the beam
25 spot may be scanned over its high-precision surface. Five axis device mount 1122 may
26 be arranged similarly to exemplary motor apparatus 700 illustrate in Figure 7 and
27 described in detail above. Five axis device mount 1122 desirably has motion stages to
28 control motion of device 1128 in five axes: three orthogonal linear translation stages;
29 Θ rotational stage 1126, which may be coupled to the three orthogonal linear
30 translation stages, to rotate the device about a Θ axis orthogonal to beam path 1101;
31 and Φ rotational stage 1124, coupled to Θ rotational stage 1126, to rotate the device
32 about a Φ axis which is orthogonal to the Θ axis and varies as the Θ rotational stage is
33 rotated. A holder (not shown) coupled to Φ rotational stage 1124 to hold device 1128
34 is also provided in five axis device mount 1122.

35 **[0094]** It is noted that Θ rotational stage 1126 may allow rotation of device
36 1128 through an angle of substantially 180°. This angle may be reduced depending on
37 the space required for objective lens 1120 (or multi-position in situ diagnostics

1 apparatus 1200).

2 **[0095]** In an exemplary embodiment, Φ rotational stage 1124 may be a spindle
3 motion stage as shown in Figure 11. Processor 1130 may control this spindle motion
4 stage to rotate device 1128 about the Φ axis at a substantially constant angular rate.
5 As described above, the constant angular rate is desirably such that the scan rate of
6 the beam spot over the high-precision surface is less than one half of the diameter of
7 the beam spot times a repetition rate with which pulses of laser light irradiate the high-
8 precision surface.

9 **[0096]** In another exemplary embodiment of the present invention each of the
10 three orthogonal linear translation stages may include a linear position sensor to sense
11 the linear position of the corresponding linear translation stage, Θ rotational stage 1126
12 includes a Θ position sensor electrically coupled to the processor to sense its Θ
13 position; and Φ rotational stage 1124 includes a Φ position sensor electrically coupled
14 to the processor to sense its Φ position. All five of the position sensors are electrically
15 coupled to processor 1130. Processor 1130 may determine the scan location of the
16 beam spot on the high-precision surface based on the predetermined surface design
17 shape, the three orthogonal linear positions sensed by the three linear position sensors,
18 the Θ position sensed by the Θ position sensor, the Φ position sensed by the Φ position
19 sensor, and, if it has been measured, the initial beam alignment. Processor 1130 may
20 also determine the angle of incidence of the pulses of laser light with the high-precision
21 surface from this data.

22 **[0097]** Processor 1130, which may include at least one of: a general purpose
23 computer; a digital signal processor; special purpose circuitry; and/or an application
24 specific integrated circuit, may use this information to control a number of parameters
25 of the laser machining process.

26 **[0098]** Exemplary parameters that processor 1130 controls may include: the
27 pulse energy of the pulses of laser light; the diameter of the beam spot; the pulse train
28 of the pulses transmitted by shutter 1104; which portions of the high-precision surface
29 are scanned; the scan rate; and the polarization of the pulses of laser light. In one
30 exemplary embodiment, the pulse energy of the pulses of laser light at a machining
31 energy level and a diameter of the beam spot such that each pulse of laser light ablates
32 an ablation depth of device material from the high-precision surface. Desirably, the
33 ablation depth may be in the range of about .01 μ m to 10 μ m. Smaller ablation depths
34 may improve the shape form accuracy of the high-precision surface, but larger ablation
35 depths allow for more rapid removal of large surface errors. The processor may be
36 used to reduce the ablation depth depending of the deviation of the high-precision
37 surface from the desired shape form.

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1 **[0099]** Shutter 1104 and five axis device mount 1122 may be controlled in
2 tandem such that predominantly only the portions of the high-precision surface that
3 deviate from the predetermined surface design shape are irradiated by the laser pulses.
4 Desirably shutter 1104 includes a high speed electro-optical pulse picker that processor
5 1130 may control to: selectively transmit individual pulses or groups of pulses of laser
6 light when the scan location is on one of the portions of the high-precision surface that
7 deviates from the predetermined surface design shape; and block pulses when the scan
8 location is on other portions of the high-precision surface.

9 **[00100]** In one exemplary embodiment, processor 1130 may be used to control
10 the motion stages of five axis device mount 1122 to maintain the angle of incidence on
11 the pulses on the high-precision surface at substantially 0° (i.e. normal to the surface)
12 as the beam spot is scanned over the portions of the high-precision surface that
13 deviate from the predetermined surface design shape.

14 **[00101]** In another exemplary embodiment, the angle of incidence is allowed to
15 vary and processor 1130 controls polarization control means 1110 to adjust the
16 polarization of the pulses of laser light. The polarization of the pulses of laser light may
17 be adjusted such that the pulses are elliptically polarized in the beam spot with a major
18 polarization axis orientation and an ellipticity of the polarization selected to reduce
19 stimulated Wood anomalies from ablation of the high-precision surface based on the
20 angle of incidence.

21 **[00102]** The exemplary laser machining system may also include an assist gas
22 chamber enclosing device mount 1122 and/or an assist gas jet to blow assist gas over
23 the high-precision surface. The use of such assist gasses may be useful in laser
24 machining process as described above. Figure 13 illustrates exemplary assist gas
25 chamber 1300, which is shown as surrounding both device mount 1122 and objective
26 lens 1120, as well as assist gas jet 1304. Exemplary assist gas chamber 1300 includes
27 transparent window 1302 aligned with beam path 1101 to transmit the pulses of laser
28 light.

29 **[00103]** Figure 14 illustrates exemplary improved aspherical lens 1400 for use
30 with short wavelength light. High-precision surfaces 1402 and 1406 of improved
31 aspherical lens 1400 may be formed using the exemplary system of Figure 11 and the
32 exemplary methods described above. This exemplary lens may be formed of a lens
33 material, such as glass, sapphire, plastic, or a combination thereof. The two light
34 refracting surfaces 1402 and 1406 of aspherical lens 1400 desirably have surface
35 shapes that match respective predetermined surface design shapes (shown as dashed
36 lines 1404 and 1408) with a maximum deviation of less than about 1 μ m, desirably less
37 than about 0.1 μ m, and preferably less than about 0.05 μ m. These deviations being

1 measured normal to the desired surface. Circles 1410 illustrate two exemplary
2 deviations of the light refracting surfaces 1402 and 1406 from their respective
3 predetermined surface design shapes that may remain in a completed exemplary lens.
4 It is noted that these deviations are not drawn to scale for illustrative purposes.

5 **[00104]** An exemplary aspherical lens may be formed by directly machining the
6 lens material to form the two light refracting surfaces of the lens. Alternatively, such
7 exemplary lenses may be mass produced using compression molds that have been
8 machined to match the desired lens surfaces. Prior art methods to form these
9 surfaces, such as mechanically grinding or cutting the surfaces, are described above
10 with reference to Figures 1A, 1B, and 2. These prior art methods leave spiral tooling
11 marks on the surface that deviate from the desired surface shape form. Additionally as
12 describe above vibrations of the shaft and other problems during mechanical
13 processing of the surface may lead to other less regular surface shape deviations. The
14 magnitude of these tooling mark deviations may be undesirably large, e.g. on the order
15 of 100 μ m. Careful grinding or cutting of the surface may reduce the magnitude of
16 these tooling marks, as may possible additional mechanical polishing processes, but
17 reduction of these tooling marks such that the maximum deviation of the surface shape
18 from the surface design form is .2 μ m or less may prove difficult. In the case of short
19 wavelength lenses and compression molds to form these lenses, deviations of .2 μ m,
20 particularly in a periodic pattern, may lead to undesirable diffraction and scattering of
21 the short wavelength light.

22 **[00105]** Mechanical polishing and other mechanical processing steps may lead to
23 other mechanical processing marks in addition to tooling marks. These other
24 mechanical processing marks may include scratches, radial marks, and cross-hatched
25 marks depending on the types of mechanical processing and/or polishing performed.
26 The exemplary laser machining methods of the present invention allow for the
27 reduction of all of these varieties of mechanical processing marks, including tooling
28 marks. Desirably, these exemplary laser machining methods may leave, at most,
29 traces of the mechanical processing marks that deviate from the desired surface shape
30 form by less than 1 μ m, desirably less than .1 μ m, preferably less than .05 μ m.

31 **[00106]** Exemplary aspherical lens may have other deviations due to material
32 defects and/or processing that may be reduced using the exemplary methods of the
33 present invention as well.

34 **[00107]** Although both exemplary light refracting surfaces 1402 and 1406 are
35 shown as having an aspherical shape in Figure 14, it may be understood by one skilled
36 in the art that an aspherical lens may be formed with only one aspherical light
37 refracting surface.

1 **[00108]** Figure 15 illustrates a similarly improved exemplary asymmetric lens for
2 use with short wavelength light 1500. This exemplary asymmetric lens includes top
3 asymmetric surface 1502, with deviation 1514 from predetermined asymmetric surface
4 design shape, and bottom flat surface 1506. The asymmetry of this exemplary lens is
5 based on the differing curvature of surface 1502 in first lens section 1510 and second
6 lens section 1512, which are separated by line 1508. This creates two lens areas
7 having different focal lengths. This asymmetry has been selected for ease of
8 illustration and is not meant to be limiting. Other asymmetric lens surfaces, including
9 surfaces of compound lens and multi-function optics lens, may be formed as well.

10 **[00109]** As described above with reference to Figure 14, the surfaces of an
11 asymmetric lens may have deviations due to mechanical processing marks from various
12 mechanical processes that may be reduced, or eliminated, using the exemplary laser
13 machining methods of the present invention.

14 **[00110]** Figure 16 illustrates an improved compression mold for short wavelength
15 aspherical lenses. Although the exemplary compression mold shown in Figure 16
16 includes mold body 1600 and release film 1602, it is contemplated that release layer
17 1602 may be omitted, particularly if mold body 1600 is formed of a material with good
18 release properties.

19 **[00111]** Mold body 1600 formed of a mold material, including at least one of:
20 tungsten-carbide; sapphire; a solid state carbon material; Al_2O_3 ; Cr_2O_3 ; SiC ; ZrO_2 ;
21 Si_3N_4 ; TiN ; TiC ; BN ; Ni ; Cr ; Ti ; W ; Ta ; Si ; glass; a cermet incorporating TiN , TiC , Cr_3C_2 ,
22 and/or Al_2O_3 ; and/or an alloy incorporating at least one of Ni , Cr , Ti , W , Ta , or Si . Mold
23 body 1600 includes mold surface 1604 which has an aspherical mold surface shape that
24 matches predetermined aspherical surface design shape 1606 with a maximum
25 deviation of less than about $1\mu\text{m}$, desirably less than about $0.1\mu\text{m}$, preferably less than
26 about $0.05\mu\text{m}$. Circle 1610 illustrates a deviation between mold surface 1604 and
27 predetermined aspherical surface design shape 1606.

28 **[00112]** As described above with reference to Figures 14 and 15, the surfaces of
29 a compression may have deviations due to mechanical processing marks from various
30 mechanical processes that may be reduced, or eliminated, using the exemplary laser
31 machining methods of the present invention.

32 **[00113]** Additionally, it is noted that a number of these mold materials such as
33 tungsten-carbide, steel, and solid state carbon materials do not machine well with
34 diamond tools. Mechanically roughing out compression molds from these materials
35 using other tools, such as tungsten turning points and/or grinding wheels may lead to
36 poor quality surface shape forms. Still, these materials may have desirable properties
37 for use in compression molds. Poor quality surfaces having large deviations from

1 predetermined aspherical surface design shape 1606 in compression molds formed of
2 these materials may be improved using one of the exemplary laser machining method
3 of the present invention, allowing use of these mold materials in high-precision
4 compression molds.

5 **[00114]** Release film 1602 is formed on mold surface 1604 of mold body 1600,
6 with release surface 1612 opposite the mold surface. Release film 1602 may be
7 formed of one or more of: nickel, titanium, niobium, vanadium, molybdenum,
8 platinum, palladium, iridium, rhodium, osmium, ruthenium, rhenium, tungsten, and
9 tantalum.

10 **[00115]** Similar to mold surface 1604, release surface 1612 has an aspherical
11 release surface shape matching predetermined aspherical surface design shape 1614
12 with a release surface maximum deviation of less than about $1\mu\text{m}$, desirably less than
13 about $0.1\mu\text{m}$, preferably less than about $0.05\mu\text{m}$. Circle 1616 illustrates a deviation
14 between release surface 1612 and predetermined aspherical surface design shape
15 1614. It is noted that predetermined aspherical surface design shape 1606 of the mold
16 body and predetermined aspherical surface design shape 1614 of the release film are
17 typically identical.

18 **[00116]** It is contemplated that similar compression molds may be formed for
19 short wavelength asymmetric lenses or various microstructure for which surface design
20 shapes having micron accuracies are desired. It is also contemplated that the a high-
21 precision release film for a compression mold, such as release film 1602 may be
22 formed on a lower quality mold body and the shape form of the release film improved
23 using one of the exemplary laser machining method of the present invention to achieve
24 a desired match to the predetermined surface design shape.

25 **[00117]** Figure 17 illustrates another issue that may be important for the design
26 of high-precision compression molds. The processing of mold body 1600 leads to the
27 creation of damage layer 1700 on mold surface 1604. This damage layer is a portion
28 of the mold material that has been changed during the processing of the mold surface.
29 For example, the change may be a change in the crystal structure of the mold material,
30 oxidation of the material, accumulated stress and deformation or distortion of the
31 material, recasting of the material, etc. This damage layer may be caused by
32 mechanical, chemical, thermal, laser, or other processing of the surface.

33 **[00118]** This damage layer may cause a number of problems for the compression
34 mold. For example, if damage layer 1700 is an oxide layer, a release film layer may
35 not adhere well to mold surface 1604. The film layer may stick but not be able to bear
36 the force necessary for compression molding and may separate from the mold surface
37 during use. If no release film layer is formed on the mold surface, damage layer 1700

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1 may change the surface performance, possibly sticking to the material being molded or
2 mechanically failing during the compression molding process. Additionally, the
3 compression mold may be heated during use. Accumulated stress or strain in damage
4 layer 1700 may be released by heating, deforming the surface shape. Therefore it is
5 desirable to reduce this layer as much as possible. Mechanical and/or chemical
6 processing of surfaces may lead to significant damage layers, possibly several microns
7 thick. Laser and other radiant energy based processing methods may cause damage
8 layers due to heating of the material in a heat affected zone around the irradiated
9 material. Ultra-fast laser machining causes less heating of surrounding material, thus
10 significantly reducing the size of the associated heat affected zone. The exemplary
11 laser machining methods of the present invention may produce exemplary compression
12 mold with a damage layer greatly reduced as compared to other processing methods.
13 For example, a damage layer 10nm thick or less may be produced using an exemplary
14 ultra-fast laser processing method of the present invention.

15 **[00119]** Although many exemplary embodiments of the invention are described in
16 terms of refining a lens mold or a lens, it is contemplated that the exemplary systems
17 and methods described herein may be used to refine any feature formed in or on a
18 material.

19 **[00120]** Although illustrated and described above with reference to certain
20 specific embodiments, the present invention is nevertheless not intended to be limited
21 to the details shown. Rather, various modifications may be made in the details within
22 the scope and range of equivalents of the claims and without departing from the
23 invention.